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Working Memory: Beyond Baddeley and Hitch

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Commentary on Cognitive Classic Paper:

Baddeley, A.D. and Hitch, G.J. (1974). Working Memory. In G. Bower (ed.), *The Psychology of Learning and Motivation, vol. VIII*, 47-90, New York: Academic Press.

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Background

Crucial for every day functioning is the human ability to retain information on a temporary basis and to keep track of what we are doing moment to moment, allowing completion of a current task or to function in a novel environment. Information is held for only a few seconds and continually updated, so forgetting of details is almost immediate. For example, in order to understand the text you are reading now, it is important to remember the text that you have just read, and the most recently read text is continually being updated as you progress through the document. Likewise, successful driving on the motorway requires continual monitoring of the position of nearby traffic and this is continually updated in memory with rapidly changing traffic patterns. Normally, there is no requirement to retain precise details such as the exact wording and font of the text read 10 minutes ago, or the precise position, model and colour of the car that was overtaking 15 minutes ago. Those details are important at the time, but not subsequently, and so are held for just a few seconds and then are forgotten as the information is updated.

This ability to retain, manipulate and update information on a moment to moment basis is often referred to as working memory, a concept that was first explored in depth by two UK based researchers, Alan Baddeley and Graham Hitch working in the early 1970s in the United Kingdom at the Universities of Sussex and Stirling, then at the Medical Research Council Applied Psychology Research Unit in Cambridge (now known as the Cognition and Brain Sciences Unit).Working memory is used for almost every daily activity; mental operations during mental arithmetic, navigating around unfamiliar environments, keeping track of current intentions and the flow of a conversation, making a meal, creative thinking, or keying a telephone number. A joint publication in 1974 by Baddeley and Hitch broke away from traditional experiments at the time on the much narrower concept of short-term memory, and laid the foundations for what is now over 40 years of research on working memory. In the two decades prior to their 1974 paper, research on short-term memory worldwide had focused on immediate memory for sequences of verbal material such as letters, numbers and words. Baddeley and Hitch put their heads above the scientific parapet by asking what a short-term memory system would be for. They asked why humans would have a need for a system that had previously been studied by asking people to remember lists of words, letters and digits. It seemed unlikely that evolution had resulted in a system that helps us remember telephone numbers and shopping lists. Their 1974 paper explored in detail the extent to which a verbal short-term memory might be important for everyday tasks that should be supported by working memory, such as understanding language and logical reasoning.

The concept of a temporary memory system that supports moment to moment human cognition has been around since the work of the British philosopher John Locke, writing in 1690, who referred to 'contemplation' as 'keeping an idea actually in view' in contrast to the 'storehouse of ideas', which is now referred to as long-term memory. Two centuries later, the American psychologist William James (1890/1905) referred to temporary memory as 'Primary Memory', and long-term memory as 'Secondary Memory'. In 1958, the British researcher Donald Broadbent referred to a short-term store that acted as a limited capacity temporary memory buffer between sensory input and longer term memory. Broadbent proposed that this temporary memory system was also closely involved in controlling attention to some of the incoming information, while acting to filter out information that was not needed. During the 1960s, two American researchers, Waugh and Norman (1965), adopted the terms Primary Memory and Secondary Memory, specifying that Primary Memory for sequences of words, letters and numbers was a system that was limited in capacity, and that information it held could be displaced by new material unless the items were rehearsed by repeating the sequence mentally or aloud. For Waugh and Norman, rehearsal was also the means by which information was copied into Secondary Memory to be retained over longer time periods.

The term 'working memory' was first given a passing mention in 1960 in a book by Miller, Galanter and Pribram, but they did not elaborate or test the concept. A much more detailed exploration appeared in a 1968 research report by Atkinson and Shiffrin who developed Broadbent's (1958) ideas regarding the need to include control processes for selection of material to be retained, and proposed that these would also include encoding, rehearsing, manipulating and retrieving as well as storing information on a temporary basis. They focused again on memory for verbal material and suggested that people could strategically focus on the control processes with a consequent reduction in memory capacity, or could store more verbal material but reduce their capacity to undertake control processing. Like Broadbent ten years earlier, Atkinson and Shiffrin viewed their concept of working memory as a temporary work space that received information directly from sensory input (primarily vision and hearing), processed that information and transferred some of the information into a long-term store. Their view is illustrated in Figure 1a.

Figure 1a and 1b about here

Detailed description

In their seminal 1974 paper, Baddeley and Hitch noted that there was remarkably little experimental evidence for the idea that a working memory included control processes involved in storage (learning) and retrieval from long-term memory or other abilities such as understanding language or logical reasoning. Of the evidence that was available, several previous research findings could not easily be explained by the Atkinson and Shiffrin proposed theory of working memory. For example, studies by Patterson in 1971 had shown that remembering a plan for retrieving information from long-term memory was unaffected by asking people to count backwards. Other studies by Brown in the UK in 1958, and a year later by Peterson and Peterson in the USA showed that the number of letters and words that can be remembered is greatly reduced if participants in the experiments are asked to count backwards after they have been given a verbal sequence to recall, but before they are asked to retrieve the sequence. So, backwards counting affects short-term verbal memory but not working memory for a control process.

Even more problematic for the Atkinson and Shiffrin theory was evidence from studies of people who suffered from very specific short-term memory impairments following localized brain damage. Baddeley and Hitch referred to one individual known by the initials ‘KF’, who was studied by Warrington and Shallice in the early 1970s in London, UK. KF had a very severe short-term verbal memory deficit that was specific for word sequences. For example, after hearing a random sequence of numbers such as 4-9-6-3-5-1, he had great difficulty in remembering more than one or two of the numbers (e.g. 4-9). A healthy adult typically can remember more than 5 random numbers. However, despite this problem, KF had no difficulty in understanding language and holding conversations, in learning new information, and in retrieving information from long-term memory. In addition, KF could remember more numbers if he could read them rather than listen to them. When he made errors, these tended to be based on what the words and numbers looked like, rather than what they sounded like. This suggested the use of some form of visual short-term memory. So, KF had a specific problem with verbal short-term memory, while the remainder of his working memory was intact.

The pattern of impairments and sparing of memory and cognitive ability in patient KF raised several problems for the Atkinson and Shiffrin theory. First, if there is a general purpose short-term memory system that supports processing and temporary storage of information, then damage to this system should be associated with impairments of the processing abilities and memory, and for non verbal as well as verbal material. Yet, KF had no difficulty with processing for language understanding, and his ability to remember material presented visually appeared to be largely intact. Only his ability to repeat back verbal sequences that he had heard was severely impaired. Over the subsequent decades, largely inspired by the Baddeley and Hitch (1974) paper, multiple studies of other patients with specific short-term verbal memory deficits have been reported. This evidence demonstrated clearly that short-term memory for words could be damaged independently of short-term memory for visually presented material, and independently of other important aspects of human cognition. That is, contrary to Atkinson and Shiffrin's view, the control processes could be separated from short-term memory rather than memory and processing both relying on the same cognitive system. This led Baddeley and Hitch to suggest that control processes might be part of executive processes (central executive in Figure 1b) which interact with, but are separate from a verbal short-term memory, and possibly also from a visual short-term memory.

A second problem for the Atkinson and Shiffrin theory that was not specifically addressed by Baddeley and Hitch, but was later noted by Logie in 1995, and subsequently in a joint paper by Baddeley and Logie in 1999, is that if working memory acts as a form of workspace or gateway between sensory input and long-term memory, then damage to the working memory system should prevent access to long-term memory for interpreting sensory input. It is also clear that the contents of working memory are not raw sensory images, but that sensory input accesses and activates (makes available) stored knowledge in long-term memory about sounds or combinations of lines and shapes, and the words, letters or numbers that are represented by those sounds and shapes *before* any information is available in working memory. If this was not the case then the contents of working memory would be meaningless. We only know that particular sounds and shapes represent words, letters and numbers because we have learned, and have in our store of knowledge that, for example the shape 'A' is the first letter in the alphabet with a particular combination of lines on the page and particular ways in which that letter should sound when pronounced. In other words, working memory cannot be placed between sensory input and long term memory, but rather deals with information that is activated from long-term memory. This alternative route to working memory is illustrated in Figure 1b. Note from the Figure that working memory is seen here not as simply the currently activated material in long-term memory (referred to as 'stored knowledge' in the figure). Evidence from studying patients such as KF, but also from experimental studies with healthy adults (reviewed in Baddeley & Logie, 1999; Logie 1995; 2011a;b) point to the idea shown in Figure 1b that working memory is a set of systems that is separate from long-term memory (the store of knowledge, skills and experiences accumulated over the lifetime), and receive the information currently activated from the knowedge store, retain that information on a temporary basis, and process it according to current task demands.

The primary focus for the 1974 classic paper was a series of experiments to investigate in much greater depth than in previous studies whether short-term memory that had been shown to be important for retaining short verbal sequences might also be important for reasoning and understanding language. One set of their experiments used a simple reasoning task in which experimental participants had to decide whether or not a sentence was a true description of the order of a pair of letters. For example 'B follows A -AB' would be true, whereas 'A follows B - AB' would be false. Some of the sentences were more difficult than others, for example 'A is not followed by B - BA' is both passive and negative, whereas the first two examples are somewhat easier because they are both active and affirmative. This reasoning task shows modest correlations with general intelligence, suggesting that it does assess some complex cognitive processes. Participants were first given one or two digits as a preload (e.g. 9-4) that they had to remember. They were then given 32 of the 'AB reasoning' sentences to verify, after which they had to recall the previously presented numbers. This was compared to a condition in which the reasoning task was performed with no memory preload. Participants could recall the preload numbers perfectly and reasoning time was the same whether or not people had a memory preload. Only when the preload was increased to six items, and participants were asked to focus mainly on the reasoning task was there a drop in recall of the preload, but reasoning time was unaffected. When participants were asked instead to focus on remembering the six memory items there was an increase in the amount of time to complete the reasoning task, but memory performance was unaffected. Similar results were obtained when combining a preload with a test of language comprehension: there was no effect on memory or comprehension with a memory load of three items, but there was an effect with six items. Results for reasoning time, with and without a preload of six items are illustrated in Figure 2. Note that as difficulty of the sentences increased (from active-affirmative to passive-negative), the overall reasoning time increased. Crucially, the effect of a concurrent memory load of six items was exactly the same, regardless of the difficulty of the reasoning problem.

Figure 2 about here

Baddeley and Hitch argued that there is a short-term verbal memory system with a capacity of perhaps three or four items, that can function in parallel with the more complex processes of reasoning and language comprehension. However, when the capacity of that short-term verbal memory system is exceeded, then other control processes such as verbal rehearsal are required, and this draws on the system in working memory that is also important for reasoning and comprehension. However, the effect of overloading the memory system was the same regardless of the difficulty of the reasoning task. This suggested that the reasoning task perhaps overlapped with rehearsal of the letters or consolidation of the letters in memory, but did not overlap with short-term storage unless the memory load exceeded the capacity of the short-term storage system.

In contrast, if participants are prevented from rehearsing a verbal sequence then there is a substantial reduction in memory performance. So, in follow up experiments, Baddeley and Hitch (1974) asked volunteer participants to repeat aloud the same irrelevant word, for example ‘the-the-the’ while they were trying to store random sequences of six visually presented digits. This requirement, known as articulatory suppression, resulted in much poorer recall of the digits than when digit sequences were presented in silence. This suggests an important role for verbal rehearsal in short-term verbal memory, and led to the proposal in a paper (Baddeley, 1983) and then book on working memory (Baddeley, 1986), that short-term memory for verbal sequences might be held in what he referred to as an ‘articulatory loop’ (see Figure1b). Related findings were that sequences of words which are phonologically similar, such as ‘bat-mat-cat-sat-rat-fat’ are more difficult to repeat back in the correct order than are sequences of words that are phonologically different, such as ‘cup-tree-bread-chair-head-watch’. This is true, even when people are reading the words, and not only when they are listening to them. This suggested that the short-term memory system retains the words on the basis of their sound, thereby leading to confusions among words that are similar in sound, known as the phonological similarity effect. Experiments reported by Baddeley, Thomson and Buchanan in 1975 demonstrated that sequences of words that take a long time to say, such as ‘typhoon, Friday, harpoon, cyclone, nitrate, tycoon’ are more difficult to repeat back in the correct order than are sequences of words that take less time to say such as ‘cricket, bishop, hackle, decor, wiggle, pewter’. This suggested a further link between spoken rehearsal and verbal short-term memory, and came to be known as the word length effect. Later experiments demonstrated that the faster people can speak then the longer are the verbal sequences they can remember.Together, these findings led to a more detailed proposal in Baddeley’s 1986 book that verbal short-term memory comprises a phonological store that can retain around two seconds worth of speech, and material can be retained in that store as long as it is rehearsed mentally or aloud. Together, the phonological store and the rehearsal process were referred to as the articulatory loop, although subsequently, Baddeley changed the name of this component of working memory to the ‘phonological loop’.

Impact

The concept of an articulatory or phonological loop dominated the development of Baddeley’s ideas on working memory for two decades following the original 1974 paper. In experiments carried out during the 1980s and summarised in his 1986 book, he demonstrated that if words are presented visually, and people are undertaking articulatory suppression, then both the word length effect and the phonological similarity effect disappear. Typically, participants are asked to write down the sequence for recall to allow articulatory suppression to continue, or, if articulatory suppression stops before recall, to avoid the possibility that spoken recall might involve the articulatory loop. However, if people hear the word sequence while undertaking articulatory suppression, then long and short words are remembered equally well, but the phonological similarity effect remains. Baddeley interpreted this by suggesting that when items are presented visually, there is automatic activation of the associated phonological codes stored in long-term memory. The articulatory rehearsal process is then important for transferring those phonological codes into the phonological store. If articulatory suppresssion prevents the rehearsal process, then the phonological codes are lost, and so there is no effect of phonological similarity when the verbal sequence is recalled in writing by participants. When the items are heard, Baddeley suggested that the phonological codes from long-term memory are made available immediately to the phonological store, so the stored phonological codes generate a phonological similarity effect, even if articulatory rehearsal is prevented. However, the word length effect arises from the use of articulatory rehearsal, and because rehearsal is prevented by articulatory suppression, the word length effect cannot occur.

Articulatory suppression disrupts verbal short-term memory, but does not wipe it out, particularly when items are presented visually. This suggests there are other systems that support short-term memory that do not overlap with concurrent articulation. One suggestion was that this might be a visual short term memory. This same visual short-term memory system could have been used by patient KF to retain visually presented verbal sequences.

The possibility of a visual short-term memory system was mentioned only briefly in the 1974 paper, and the concept developed much more slowly than did the articulatory loop. Two studies by Baddeley, Grant, White and Thomson (1975), and by Baddeley and Lieberman (1980) demonstrated that the ability to retain in memory a random path around an imagined pattern of squares was disrupted by carrying out concurrent arm movement. This then linked the control of arm movement with the memory system that could retain a sequence of movements. A series of experiments published by Logie in 1986 demonstrated that retaining visual mental images was disrupted by presentation of irrelevant, random pictures of objects, but was not disrupted by presenting streams of irrelevant random spoken words. In contrast, remembering a set of visually presented words was disrupted by irrelevant spoken words but not by irrelevant pictures. This complemented other studies carried out by Salamé and Baddeley (1982) which had shown that retaining a sequence of visually presented digits was disrupted by presenting recordings of random spoken words. These sets of results pointed towards a short-term memory system for remembering movement sequences, visual images, and possibly also the visual appearance of letters and numbers, that was separate from a short-term memory system for retaining phonological codes for words. Baddeley (1983; 1986) referred to this as a visuo-spatial scratch pad, shown in Figure 1b. However, it was not until a book by Logie in 1995 that the concept of visuo-spatial aspects of working memory were explored in detail. The evidence collated at that time led to the proposed change in the direction of the information flow shown in the lower half of Figure 1b, and led to development of ideas about how visual and spatial information might be supported within working memory, illustrated in Figure 3. Logie (1995; 2003; 2011b) proposed that mental imagery was more likely to be an executive or control process coupled with activated long-term memory, and linked to conscious experience of mental images. Visual short-term memory was thought to function in an analgous way to the phonological loop, but comprised a passive and non-conscious store, the visual cache, with capacity for a single visual pattern or array of shapes limited by complexity or amount of detail, and an inner scribe that supported the retention of sequences of movements, and possibly acted as a control process to help rehearse or refresh the contents of the visual cache. Some recent evidence for this general view of visuo-spatial working memory is reported in van der Meulen, Logie and Della Sala (2009), and Borst, Niven and Logie (2012).

Figure 3 about here

The influence of the 1974 paper on the broader research community over the following two decades was largely restricted to researchers and research groups within the UK and in some countries in the rest of Europe, notably Italy. Here, the interest was on developing an understanding of what is referred to as the architecture of working memory; the general principles governing how working memory is structured, organised and how it functions in all healthy adults. In the late 1980s, Hitch (1988) explored how working memory develops in young children, demonstrating a tendency to rely on visual short-term memory for objects they have seen. It is only around 8 or 9 years of age that they spontaneously rely on the names of objects and show evidence of the effects of phonological similarity or word length. Another British researcher, Susan Gathercole worked with Baddeley (Gathercole & Baddeley, 1989; 1993) on the relationship between the phonological loop and the development of language in young children. This work demonstrated that children around age 3 or 4 who were good at repeating a nonsense word were also the children who had better language skills both at the time they were first tested and also when they were retested four years later at ages 7 or 8. This led to the idea that the ability of the phonological loop to store a completely new verbal sound sequence and repeat it back in the correct order is important for learning new vocabulary. That is, the phonological loop appeared to be one of the essential ingredients for humans to acquire language in childhood, thereby answering part of Baddeley and Hitch's original question as to why having a verbal short-term memory might be useful.

During the same period of the 1980s and 1990s, there was a rapidly growing interest in the UK in understanding the nature of memory and other cognitive impairments in adults who had suffered brain damage. There was a similar rapidly growing interest among Italian neurologists in developing cognitive tests to assess their brain damaged patients who appeared to have very specific cognitive impairments. For example, in 1975, two Italian neurologists, De Renzi and Nichelli described patients who had very specific impairments in remembering visual patterns and pathways, but had intact verbal short-term memory. Baddeley worked with another Italian neurologist (Vallar & Baddeley, 1984), in a detailed study of a patient known as 'PV', who, like patient KF mentioned above, had a very specific verbal short-term memory deficit. PV also had difficulty learning vocabulary from an unfamiliar foreign language, supporting the idea that efficient functioning of the phonological loop is important for learning new vocabulary. These results could be interpreted by suggesting the De Renzi and Nichelli patient had a deficit in the visuo-spatial scratch pad, whereas both KF and PV had deficits in the operation of the phonological store. These dissociations between patients are very difficult to explain within an Atkinson and Shiffrin type model which would predict that an impairment of short-term verbal memory should be associated with impairments of visual short-term memory and of control processes because they all rely on the same part of the cognitive system. The results are also incompatible with the idea that working memory is simply the activated information from long-term memory, because if this were the case, then KF, PV and the De Renzi and Nichelli patient should also have problems in accessing long-term memory. But in all these, and many similar cases of short-term memory impairment, long-term memory access is intact. A review of studies of patients with short-term verbal memory impairments is given by Vallar and Shallice (1990). A review of studies with patients who have short-term visual memory impairments is given by Logie and Della Sala (2005).

The common interest across Europe led to other very successful collaborations between British cognitive psychologists and Italian neurologists, and some of the collaborations formed in the 1980s continue in 2014. For example, in 1986, Baddeley and Logie, working with Italian neurologists Spinnler, Bressi and Della Sala compared healthy younger and older adults with patients suffering from Alzheimer’s disease on their ability to perform two tasks at the same time. The tasks were chosen to rely respectively on the phonological loop and the visuo-spatial scratch pad, and to avoid input and output conflicts (heard input with spoken output for digits and visual presentation for input with arm movement for output). They found that healthy adults, old or young, could listen to and repeat back sequences of random digits (phonological loop) at the same time as using a stylus to follow a randomly moving target around a computer screen (scratch pad), with very little reduction in verbal memory or tracking performance compared with doing each task separately. The Alzheimer patients could perform each task on its own, but had very considerable difficulty performing the two tasks together. Della Sala and Logie continued the collaboration, demonstrating the same and similar findings across multiple experiments (e.g. Della Sala, Foley, Parra & Logie, 2011; Logie, Cocchini, Della Sala & Baddeley, 2004) and recently have been developing versions of the original laboratory tasks as formal clinical tests to help diagnosis of Alzheimer's disease.

In 2000, Baddeley proposed the addition of another component of working memory, the 'episodic buffer' that was thought to be a temporary memory system for integrated representations that, for example, maintains the meaning of an ongoing conversation, but also holds combinations (or temporary bindings) of colours and shapes, such as remembering that you just saw a red circle and a green triangle rather than a green circle and a red triangle. Subsequent studies on the concept of the episodic buffer have shown that it can function automatically without reliance on control processes. Information in the buffer also appears to be fragile and is easily overwritten by new information (e.g. Allen, Baddeley & Hitch, 2006; Logie, Brockmole & Vandenbroucke, 2009). A recent brain imaging study (Parra, Della Sala, Logie & Morcom, 2014) suggested that areas in the frontal areas of the brain may be recruited for undertaking the temporary binding, whereas more posterior areas of the parietal cortex are involved in temporary memory for single features such as shape only. However, it remains an open question as to whether temporary memory for these kind of bindings requires the concept of an episodic buffer rather than being a function of, for example a visual short-term memory system as part of the working memory system coupled with activated long-term memory.

Critique

The Baddeley and Hitch (1974) paper has been, and continues to be frequently cited by researchers worldwide as the primary source for the working memory concept. So it remains highly influential. However, even after the accumulation of four decades of evidence, there has been and remains considerable reluctance among most North American researchers and some European researchers to accept the Baddeley and Hitch (1974) core proposal that short-term memory functions separately from control processes, or that there might be separate verbal and visual short-term memory systems. Indeed, there are now multiple research groups whose work is focused on exploring how the Baddeley and Hitch proposal might be wrong. Here, the research has been heavily influenced by the view of working memory as a combination of memory and control processes sharing a common resource, which were largely ideas proposed by Broadbent (1958) and by Atkinson and Shiffrin (1968), and shown to be problematic by Baddeley and Hitch (1974).

There has been less interest in North America in using cognitive theories to help understand the impact of specific forms of brain damage, or to understand how different systems in the brain work together to support every day activities. As a result, working memory in North America has come to be viewed as a general mental capacity for holding information on a temporary basis in the presence of ongoing processing and other distracters. One major influence came from a paper published in 1980 by two North American researchers, Daneman and Carpenter. They developed a sentence span test in which participants were asked to read a series of sentences and for each sentence they had to remember the final word. After all the sentences had been read, participants were asked to recall all of the final words in the order in which they had been presented. The number of sentences, and hence the number of words to be remembered increased as this process was repeated until the participant was unable to recall the final words correctly. The maximum number of words that people can recall in the task varies from person to person, and Daneman and Carpenter showed that people who were good at this task also were good at a wide range of other complex tasks such as language comprehension. Likewise, people who were poor at the sentence span task also were poor at language comprehension. The researchers argued that their sentence span task was measuring a fundamental human mental ability and they referred to this as working memory.

Subsequent studies developed different variations of the task. Most notably US researcher Randall Engle and colleagues (e.g. Engle, Kane & Tuholski, 1999; Turner & Engle, 1989) who developed a version that they called ‘operation span’ in which people were given simple arithmetic sums, instead of sentences, followed in each case by an unrelated word. Variation in how many words people could remember when interspersed by arithmetic showed good correlations with performance on language comprehension, but also on a wide range of other tests of cognitive ability, including general intelligence and performance in exams. This approach of using individual differences in memory performance in the presence of a distraction continues to dominate working memory research in North America, where the focus is on understanding why it is that people vary in their capacity for these tasks, and what that variation tells us about the underlying factors which determine that capacity. There is less interest in the underlying range of resources that might be deployed to perform these tasks. In terms of the Baddeley and Hitch view of working memory, the individual differences measures are reflecting the operation of both control processes and short-term memory, or in other words, the excutive resources and the phonological loop. This was recognised in passing by Engle and Conway (1998). More recent research on the operation span has shown that it correlates highly with measures of access to long-term episodic memory (e.g. Unsworth & Engle, 2007). Other research has shown that operation span measures do not correlate highly with another widely used measure of working memory, known as the n-back task (Kane, Conway, Miura & Colflesh, 2007) in which participants have to continually update their working memory for recently presented items. These findings suggest that operation span and sentence span are measuring a general capacity of the whole cognitive system, and in particular the ability to encode and retrieve information in long-term memory. This would explain why these measures correlate with general intelligence and a wide range of other complex abilities. However, the findings also suggest that although these are referred to as working memory capacity measures, they might not actually be measuring working memory. This argument is explored in detail by Logie and Niven (2012).

A further difficulty with the individual differences approach noted by Logie (2011a) is that it relies on the maximum score that participants can achieve on the test they are given, and how these scores vary from one person to another. However, this means that any cognitive abilities that are required for task performance at less than their maximum capacity will be completely invisible. For example, reading sentences and remembering the final word from each sentence requires our ability to see and our knowledge of the language in which the sentences are shown. However, the task is well within the visual and language abilities of most people. Only the ability to remember and repeat back the words will vary from one person to another. This would tell us nothing about the contribution from other abilities that are required to do the task. There could also be modest contributions from a visual short-term memory system as people move their eyes across the words of the sentences, but this too would not be evident from the memory scores. In other words, measuring individual differences does not tell us about the range of working memory and other cognitive abilities that are available for performing a task, and developing a theory of working memory based on individual differences in maximum test scores is a blunt instrument for exploring the nature of working memory. This approach does allow us to predict who will do well or who will do poorly when they perform other very demanding tasks, but might have little to say about how we perform daily activities that are well within our working memory capacities. A related problem is illustrated by considering how human biology is assessed. We could have a measure of our general health and fitness, and this might predict how quickly we might run 100 metres. However, this would tell us nothing about the specific functioning of the heart, the liver, the kidneys, or the lungs. Nor would it reveal what is required for us to walk 100 metres at a leisurely pace. So too, a general measure of working memory might predict how well we will perform in University exams, but will tell us nothing about how different aspects of working memory function, or how they support our thinking and memory when chatting to our friends, reading a newspaper, driving to work, or typing numbers on a cash machine.

Another prominent North American working memory researcher, Nelson Cowan, was more directly influenced by the earlier work of Broadbent (1958), and in 1997, Cowan proposed a theory linking working memory closely with the control of attention (see also Cowan, 2005). His view was that working memory comprised the currently activated information from long-term memory, coupled with a limited capacity focus of attention on a small subset of that activated information. This was a hybrid of both theories in Figure 1, in that it retained the idea from Broadbent that working memory relies on a single limited capacity resource (the focus of attention), but it also incorporated an important feature of the lower half of Figure 1b, by suggesting that the contents of working memory are activated from long-term memory, not directly from sensory input. However, like Atkinson and Shiffrin, Cowan's approach does not incorporate any clear distinction between control processes and temporary memory, and does not readily explain the specific verbal or visual short-term memory impairments in patients. Also, Cowan does not view working memory as clearly separate from the activated contents of long-term memory.

The actual theoretical proposal in Baddeley and Hitch (1974) continues to be influential for groups in the UK and in other countries of Europe and to a certain extent in Asia and in Australia, as well as for some groups in North America. In 2013, Alan Baddeley had twice as many citations worldwide than he did in 2003, so the influence is growing, not waning, and the 1974 paper alone has been cited over 9000 times since its first publication. However, it is not clear that authors who reference the 1974 classic paper have looked at the detail of the original paper, and many appear to include this reference in their papers because other researchers do so. For example, the 1974 paper is very commonly referenced as the source for the top part Figure 1b, but that figure did not appear anywhere until it was included in a paper published by Baddeley in 1983. Also, rarely do contemporary papers on working memory refer to experimental findings in the 1974 paper that are still highly relevant to contemporary debates, such as whether or not control processes and short-term memory share a common resource.

Conclusion

A major motivation for the original Baddeley and Hitch (1974) paper was to address a lack of agreement among researchers as to precisely what is meant by short-term memory, and what short-term memory might be used for. Over the 40 years since its publication, many thousands of experiments have been carried out and published, including numerous brain imaging studies. So there is no shortage of empirical evidence available. However, it is striking that 40 years later, such a wide range of different theoretical conceptions are in use, and different groups refer to rather different concepts when using the term 'working memory', even if they refer to the Baddeley and Hitch (1974) paper as the original source of the concept. So, this classic paper inspired several generations of researchers to use the concept of working memory to answer different questions, and the kinds of questions they ask tend to determine the nature of the theoretical perspective that they develop or adopt. In a recent conference, Baddeley referred to the plethora of theories as being like toothbrushes. Everyone needs one, but each person is reluctant to use one that belongs to someone else. This approach of different researchers developing their own theoretical perspective and experimental paradigms might help develop understanding of specific aspects of working memory, such as why people differ in their working memory capacity, or why we forget what we have just seen when we are distracted. Multiple papers have explored possible alternative explanations for phenomena such as the phonological similarity effect or the word length effect, suggesting that the original interpretations of these phenomena might be misleading. In some sense this is how science progresses, by refining a problem or research question and then focusing efforts on that question. However, there is a danger of missing the broader picture, and while an alternative theory might offer an alternative explanation for the specific phenomena studied, that alternative theory might not be so successful at explaining other phenomena that have been explained by the multiple component approach to understanding working memory illustrated in Figures 1b and 3, such as the specific impairments in brain damaged patients.

A major strength of the multiple component working memory approach is that it is relatively simple. A further strength is that it has been shown to be useful in explaining research results from a very wide range of research topics, for example aspects of children's language development, aspects of counting and mental arithmetic, reasoning and problem solving, dividing and switching attention, navigating unfamiliar environments, the cognitive impairments resulting from healthy ageing and from specific forms of brain damage, the ways in which people vary in their mental abilities, as well as how we keep track of our every waking moment. The longevity of a theory attests to its scientific value. The 40th anniversary of the publication of the Baddeley and Hitch 1974 paper was recently celebrated in 2014 in Cambridge, UK, at a conference that was grossly oversubscribed and had a waiting list of delegates hoping for 'standby' places. This demonstrates the continuing popularity of the topic among researchers, and the continuing substantial influence of an important scientific milestone.

Suggested further readings

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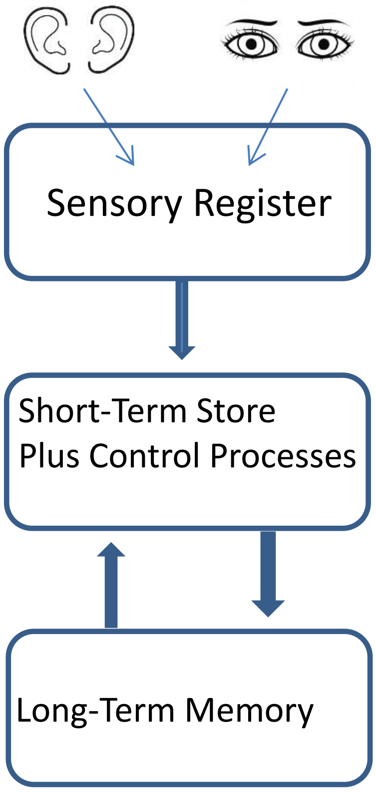
Figure Captions

Figure 1. Alternative proposals for information flow in human memory, with working memory as (a) a single flexible system supporting control processes and short-term memory that sits between sensory input and long-term memory, or (b) as a set of executive control processes plus temporary, limited capacity memory systems for verbal (articulatory loop) and non-verbal (visuo-spatial scratch pad) material (right diagram) that deals with material activated from long-term memory.

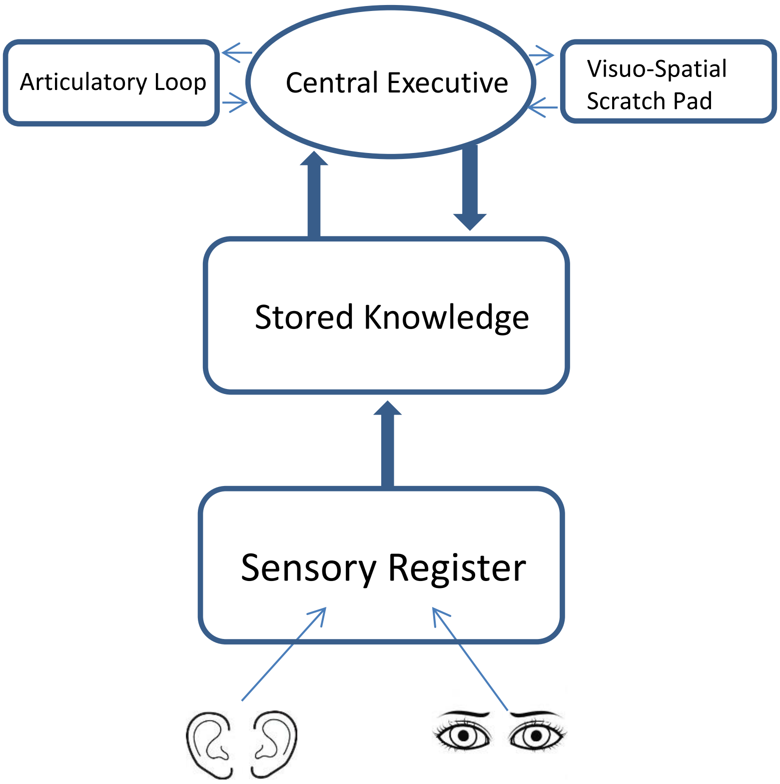
Figure 2. Mean reasoning time for different forms of reasoning problem without (control) and with a preload of six digits. Figure redrawn from Baddeley & Hitch (1974), Figure 1, with permission.

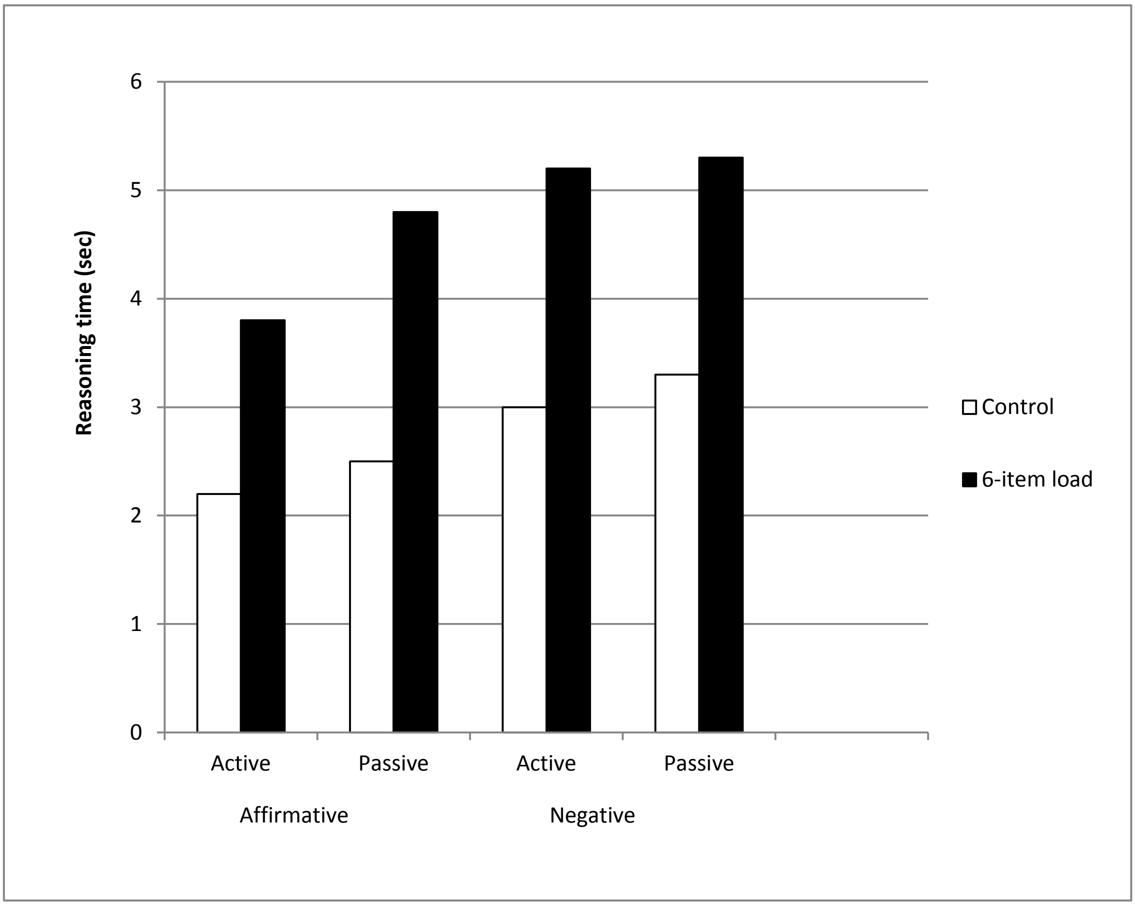
Figure 3. An illustration of working memory as multiple components originally proposed by Logie (1995). Figure reproduced from Logie (2003).

(a) Theory of Human Memory
Atkinson & Shiffrin (1968)
Based on Broadbent (1958)



(b) Working Memory theory based on Baddeley & Hitch (1974).
Updated in Baddeley (1986), Baddeley & Logie (1999), Logie (1995)





6
5
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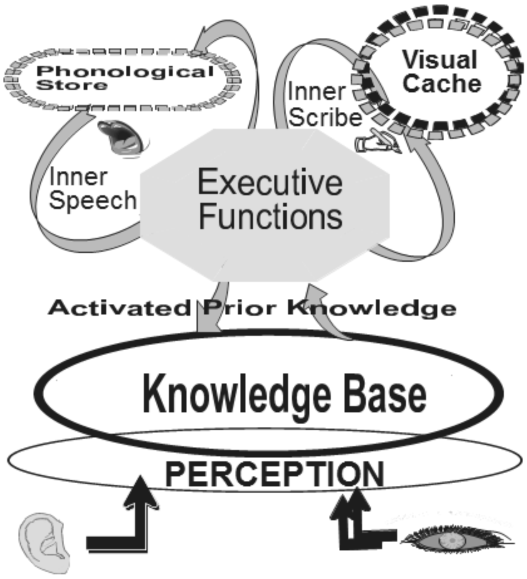
Reasoning time (sec)
Active
Passive
Active
Passive
Affirmative
Negative
Control
6-item load


Phonological Store
Visual Cache
Inner Scribe
Inner Speech
Executive Functions
Activated Prior Knowledge
Knowledge Base
PERCEPTION